Energy 74 (2014) 119–130

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Assessing the energy efficiency of a jaw crusher

Daniel Legendre*, Ron Zevenhoven

Thermal and Flow Engineering Laboratory, Åbo Akademi University, Turku, Finland

ARTICLE INFO

Article history:
Received 18 September 2013
Received in revised form
28 March 2014
Accepted 12 April 2014
Available online 19 May 2014

Keywords:
Energy efficiency
Comminution
Jaw crusher
Experiments
DEM simulation

ABSTRACT

It is well known and taken for granted that the efficiency of energy use by comminution (i.e. breaking, crushing, grinding) equipment is very low, typically less than 10%. Most of the process input power is dissipated as heat and noise and ineffective deformation of the material to be processed and the device itself. Here, a study is reported that analyses the reasons for this low efficiency and tries to give recommendations for improvement. With a lab-scale jaw crusher as a test case, an optimisation was made on how to operate it most energy-efficiently by using an evolutionary algorithm numerical method. For a selected optimised case an attempt was made to simulate the jaw crusher using a commercial software for discrete element modelling (DEM), after first simulating single particle breakage using this software. Also, some experimental results on the crushing of several ~600 g pieces of rock while measuring electric power during the process are reported.

1. Introduction

Comminution processes have always been characterized by low efficiency rates. This is mainly because for this kind of process it has traditionally been more important to obtain a determined particle size distribution than to a have low power consumption. Nowadays, however, power consumption and therefore efficiency of all kinds of equipment are becoming more important, mainly caused by the continuous increase of energy costs and efforts to minimise CO_2 emissions [1].

The dissipative nature of a comminution process results from the random application of forces inside machinery and between neighbouring particles. This random application of forces is translated mainly into noise, heat and largely elastic particle deformation and in the end only a fraction of this energy is used for the actual size reduction. In order to improve the efficiency of a comminution process it is first important to understand the actual comminution process. Then it can be estimated how variations in equipment geometry, shaft velocities, particle sizes, material properties among other variables can affect the performance of specific equipment. After this, the comminution equipment performance can be optimised. Models that take into account all relevant variables of comminution machinery performance are difficult to find [1]. A second approach aims at changing the materials properties of a rock before a comminution process. Some authors have suggested material pre-treatments that destabilise the material internal structure [1]. Nevertheless, energy usage and the nature of these methods still need to be defined properly.

The basic approach in the modelling of comminution systems is to recognise the fact that all comminution processes dissipate energy as noise and heat, while disrupting the binding forces between particles constituting the ore [2]. Depending on the process used, either a single impact or multiple impacts are applied until disintegration and size reduction reaches acceptable values.

In today's engineering world there is no good definition for the efficiency of comminution processes, although it is well known that it is an inefficient procedure if the analysis is based in power requirements only. Consequently, there is not a good perception of how much the performance of particle size reduction process can be improved.

2. Theoretical background

There have been several attempts to accurately determine the actual energy required for a comminution process. The most acceptable theory is based on the fact that in a size reduction process as the mean particle size decreases, the surface area of the particles increases. Therefore a measurement of the surface area (S) before and after size reduction would be a reliable indicator of the energy (E) used in the comminution procedure. This can be written in a mathematical form as:

$$\frac{dE}{dS} = kS^n \qquad (1)$$

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* Corresponding author. Tel.: +358 2 215 4441.
E-mail addresses: daniel.legendre@abo.fi (D. Legendre), ron.zevenhoven@abo.fi (R. Zevenhoven).

http://dx.doi.org/10.1016/j.energy.2014.04.036

where k is a constant related to the crushing strength of the rock. Different workers have determined the values of parameters “k” and “n”, with the three most important ones being: (1) Rittinger, $n = -2$, $k = C_R$; (2) Kick, $n = -1$, $k = C_K$, and (3) Bond, $n = -1.5$, $k = W_i/2$.

It has been suggested that the three approaches to prediction of energy requirement mentioned above are best applicable to certain of product size ranges. These are presented in Table 1 [3].

2.1. Bond index theory

The aim of the present work is to understand the reasons for inefficiency and to improve the efficiency of comminution machinery. Bond’s Work index coefficients cover almost the entire range of particles to be processed using commercial equipment [4]. With this theory, the energy requirements are based on experimental shaft energy measurements of comminution machinery [4]. The Work index coefficients values were then calculated and correlated to passing feed sizes that do not, however, provide any kind of information regarding particle size distributions [1]. The final form of Bond’s equation can be written as [4]:

$$E = 10CW_i\left(\frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}}\right) \quad \left(\frac{\text{kWh}}{\text{ton}}\right) \tag{2}$$

where C = a tabulated constant depending on type and condition (wet or dry) of comminution equipment, F_{80} = 80% passing sieve size of the feed, μm, P_{80} = 80% passing sieve size of the product, μm, W_i = Bond work index: the work required to reduce ore from an infinite size to 100 μm, kWh/ton. The value of W_i can be considered to be independent of any classifier placed in the circuit. In the terms F_{80} and P_{80}, the subscripts denoting the sieve size of feed and product, respectively, through which 80% of the feed and product passes. The terms $1/\sqrt{P_{80}}$ and $1/\sqrt{F_{80}}$ are dimensionless, as the number 10 represents microns.

2.2. Maximum theoretical efficiency

Although it is known that a comminution process is very inefficient in terms of energy required to generate new surface area (which could lead to the conclusion that this could be improved very much) it makes more sense to focus on a reference point for the maximum beneficial energy use for size reduction. Due to the random application of forces from the machinery to the particles, it is certain that a 100% efficiency point is something far from reality [5].

Tromans [1] defined the maximum ideal limiting efficiency (η_{Limit}), based on a compressive loading comminution machine, which generated a stress distribution inside a single particle as the result of a central crack (flaw). This implies a theoretical minimum energy usage, where the numerator of the maximum efficiency η_{Limit} in Eq. (3) represents the difference between the strain energy per unit volume in a spherical particle and the strain energy per unit volume in the same sphere with a single vertical crack or flaw, both particles being submitted to compression forces. The denominator stands for the strain energy per unit volume in a sphere with a single vertical flaw submitted to identical compression forces [1]. Finally, the expression is multiplied by a 66% factor that represents the ratio of the ellipsoid of the stress relaxation volume around the single crack and the accommodating cylinder [1]. After several mathematical deductions and certain approximations to the so-called Griffith criterion for crack propagation is obtained [6]:

$$\begin{aligned} &\sigma_x = \sigma_y = \frac{P}{\pi D^2}\left(\frac{3}{\sqrt{2}}(1-2\upsilon)\left(\frac{2}{\sqrt{2}+1}\right)\right); \sigma_z = -\frac{P}{\pi D^2}\left(12 - \frac{3}{\sqrt{2}}\right) \\ &\eta_{\text{Limit}} = \left[\frac{\sigma_x^2 - 2\upsilon(\sigma_x\sigma_y + \sigma_x\sigma_z)}{\left(\sigma_x^2+\sigma_y^2+\sigma_z^2\right) - 2\upsilon(\sigma_x\sigma_y+\sigma_x\sigma_z+\sigma_y\sigma_z)}\right] \times 66\% \end{aligned} \tag{3}$$

where P = loading force, N; D = particle diameter, m; $\sigma_{x,y,z}$ = stresses along x-, y-, z-axes, compressive or tensile, Pa, and ν = Poisson’s ratio, −, typically ranging from 0 to 0.5.

Tromans [1] found that this limiting efficiency value is a function only of the Poisson’s ratio (υ) of a certain material. The η_{Limit} definition is not influenced by other system variables such as particle diameter D or compressive force P as can be observed in Fig. 1.

Table 1
Terminology used in comminution and equation adequate coefficients use.

Size range of the product	Description	Adequate model
1−0.1 m	Coarse crushing	Kick
0.1 m	Crushing	Kick and Bond
1 cm	Fine Crushing, coarse grinding	Bond
1 mm	Intermediate grinding, milling	Bond
100 μm	Fine grinding	Bond
10 μm	Ultrafine grinding	Rittinger

2.3. Efficiency considerations

In a comminution process the energy is utilized as follows [7].

1. In producing elastic deformation of the particles before fracture occurs.
2. In producing inelastic deformation that results in size reduction.
3. In causing elastic distortion of the equipment.
4. In friction between particles and between particles and the machine.
5. In noise, heat and vibration in the plant.

Several authors [4,8,9,11,12] have given definitions of energy and power consumption efficiency although still there does not exist a commonly acceptable definition as function of particle size distributions or surface area increase. A compilation of the most widely used energy efficiency definitions is given by Legendre [5]. Nevertheless it is still a persistent problem to estimate the actual power consumption of a certain size reduction process, and how to make it more efficient [5].

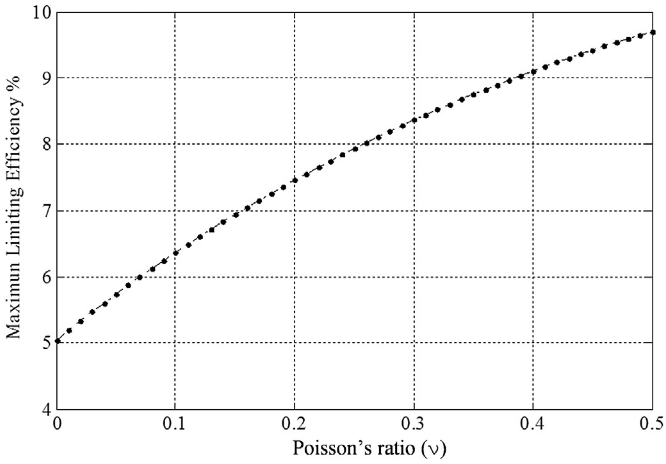

Fig. 1. Effect of Poisson’s ratio on the maximum limiting energy efficiency.